**Stony Brook University**

**Department of Electrical and Computer Engineering**

**Stony Brook, New York, 11794-2350**

# MARIACHI

## Experimental Detection of Radio Wave Reflection off a High Energy Ionization Beam

**Susan Eraly, 105283526**

**Joshua Grossberg, 104432523**

**Marcin Tkaczyk, 100755152**

## ABSTRACT

This project initially involved the detection of ultra high energy cosmic rays using the principles of passive radar interferometry. During the course of this project it was required to conclusively verify the reflection of commercial VHF signals off the ionization patch produced by a cosmic ray shower. The emphasis of the project during the second semester was hence changed to detecting radio wave reflections from a high energy ionization beam located at the NASA Space Radiation Laboratory in Brookhaven National Labs. There are primarily two coexisting periodic structures in the intensity of the ionization beam - the first at 2 MHz was unusable as the periodicity is wiped out by the electron recombination lifetime; the second at 1/3 of a Hz posed other problems as it was very small compared to the used carrier frequency of 100 MHz. Dummy experiments were set up using a time varying resistive load connected to a passive antenna as a reflecting surface. Low power reflections were successfully detected from a 1/3 Hz periodically varying surface of a biconical antenna. However reflections from the high energy ionization beam at NSRL are yet to be detected. Future work would involve attempting to detect reflections after varying the beam structure to accommodate an additional 60Hz periodicity.

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# 1 GOALS AND IMPACT

While funded by the National Science Foundation (NSF), MARIACHI (Mixed Apparatus for Radar Investigation of Cosmic-rays of High Ionization) is a full-scale research project created and directed by Brookhaven National Lab (BNL). This project is being performed by a diverse group of people from various educational backgrounds. Moreover, MARIACHI is comprised of participants whose educations range from the high school to doctorate levels. This project will significantly benefit local communities as well as the greater society. Ultimately, MARIACHI will educate high school students on basic physics, computer, and internet principles, while simultaneously accomplishing its main goal of detecting, locating, and classifying cosmic rays penetrating the Earth's atmosphere.

> "[A]mid the incessant hail of cosmic rays striking Earth's atmosphere from outer space, every now and then one comes screaming in with the energy of a walnut-sized hailstone […] Such ultrahigh-energy cosmic rays could herald bizarre astronomical phenomena or new fundamental particles, so physicists are eager to know how often they come along."

This section from [1] accurately describes the motivation for developing the MARIACHI Project. The main goal of the project is to develop and demonstrate a new technique that accurately detects UHECR, or Ultra High Energy Cosmic Rays, entering the Earth's atmosphere. Furthermore, if it's successfully developed, MARIACHI will ultimately be able to detect cosmic rays over larger detection areas, compared to previous techniques, while simultaneously assuring cost efficiency.

There is vast interest in the study of cosmic-ray physics, particularly this phenomenon; it is considered to be of great importance because its solution would provide insight into the origins and evolution of the universe. Currently, there are several theories being developed, one of which suggests that these UHECR might be new and unknown exotic particles.

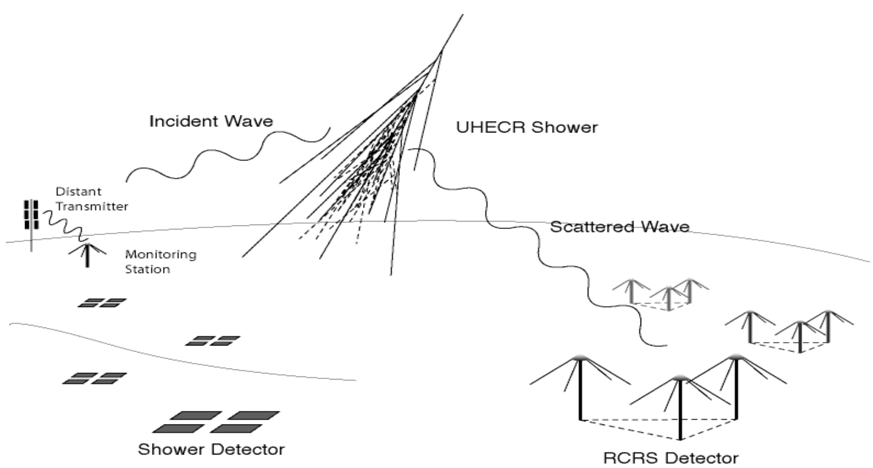


*Figure 1. The MARIACHI detection concept.*

Figure 1 depicts the proposed setup of the MARIACHI detection concept. In this illustration, scattered radio waves by the UHECR shower are detected by RCRS (Radio Cosmic Ray Scatter) stations in coincidence with ground shower array signals. UHECR with energies larger than 1 EeV ($10^{18}$eV) produce strong ionization trails in the ionosphere, which allows for the realization of the RCRS technique. When a high energy cosmic ray enters the atmosphere and creates an ionization trail, the radio waves will reflect off of this cylindrical surface and be detected by the three (3) detection stations.

Clearly, the implementation of this technique assumes the reflection to be specular rather than diffuse. In addition to the radio detection stations, there will be scintillation arrays setup throughout Long Island, at high schools participating in the project, for the purpose of redundancy. The ultimate goal is for all three stations along with the scintillation arrays to detect the same event once it occurs. After determining that the event detected was an UHECR, there is an enormous amount of information that can be extracted. Consequently, by the method of triangulation one can theoretically determine the existence of point sources in the universe.

The creation of the ionization trail has a pyramid domino affect. With each reacting particle, the ionization trail grows larger, expanding in diameter and in length. As a result, this process leaves a large "footprint" that can be detected once the particles hit the Earth's surface. Utilizing these arrays, one can be sure if the signals detected by the RADAR reflection were in fact UHECR.

# 2 BACKGROUND

The following sections describe the necessary background to the project performed.

## 2.1 SURVEY

The proposed technique, named Radio Cosmic Ray Scatter (RCRS), explores the use of reflected FM radio and television signals in conjunction with ground based scintillation arrays to improve detection of these high energy rays. In the mid-twentieth century, there were two experimental attempts to detect UHECR using the RCRS technique. Unfortunately, both experiments concluded that the observed signals were created by meteors. Clearly, this technique is optimal for meteor detection. However, major technological advances have been made in RADAR since then. Is it now possible to accurately detect UHECR using the RCRS technique?

Recently, there has been an experiment performed similar to MARIACHI. The experiment, named the Manastash Ridge Radar (MRR) experiment, was performed by the Electrical Engineering Department at The University of Washington. The purpose of MRR was to detect irregularities in the ionosphere due to aurora borealis, more commonly known as the northern lights. Although the goals of this experiment are different, the technique used is fundamentally equivalent.

MRR required the collection of reflected VHF FM signals due to aurora irregularities, whereas MARIACHI requires reflected signals due to ionization trails caused by UHECR. In the MRR experiment, phase, range, and Doppler information were gathered using multiple antennae arrays, each consisting of a Yagi and Log Periodic antenna. These antennas were used in both MRR and MARIACHI due to their desirable attributes; mainly their high directivity. Ultimately, MRR was deemed successful. This proves that the RCRS technique can be used to detect irregularities in the Earth's atmosphere.

Unfortunately, the following question still remains: does highly ionized air reflect VHF signals? Answering this question was the main focus of the 2006 Spring Semester. The experiment, which was performed at NSRL (NASA Space Radiation Laboratory), and its results will be discussed in the latter portion of this report.

## 2.2 PROJECT PLANNING

A large part of the first semester was spent planning for the project. There were weekly meetings with professor Djuric, Professor Marx, and Helio Tekai. Materials on detection theory were studied as well as papers relating to similar experiments. The experiment that served as a basis for the originally planned experiment was the Manastash Ridge Radar Experiment performed at the University of Washington. This experiment was studied in detail.

The nature of the experiment changed in the second semester. The decision was made to utilize the beam at NSRL to simulate the ionization patches formed by the UHECR's. A large amount of safety training needed to be accomplished to use the facility. Several meetings were conducted with physicists at NSRL to gain insight into the nature of the beam, particularly the periodic structure. Measurements were taken of the room dimensions, which were small in certain areas and brought about added worries concerning the ability to detect reflection. These effects of these are constraints on reflection at the required wavelength were observed at Stony Brook. More details on the final experiment are provided in section three.

# 3 SYSTEM IMPLEMENTATION AND TESTING

This chapter outlines the implementation of the experiment, the specific components used and the actual approach. The following is the block diagram of the experimental set-up.

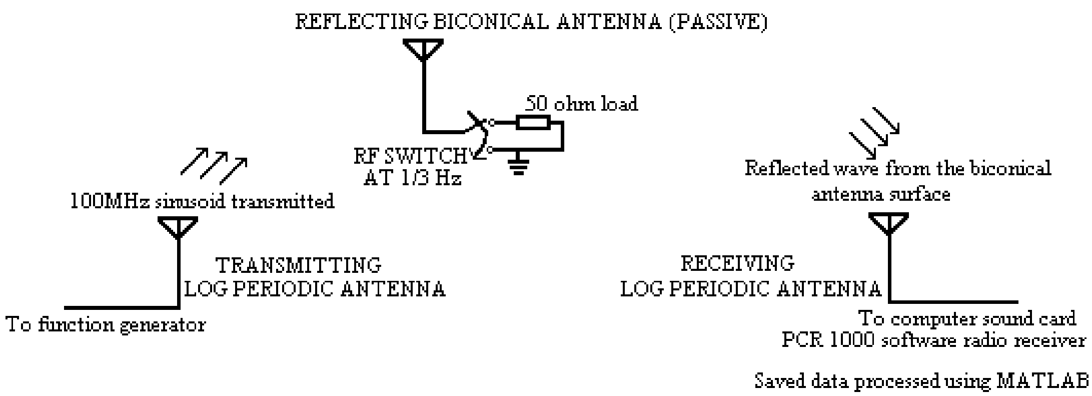


*Figure 2. Experimental Setup*

*While checking for reflections off the beam, the biconical antenna reflecting surface and RF switch are replaced by the ionization patch produced by the beam.*

## 3.1 IMPLEMENTATION PROBLEMS

At the beginning of the second semester the members of the group were informed that NSF required that there be more evidence that RF reflections could be detected off of patches of ionization. A new experiment was developed to display that reflections could occur. The ionization beam at the NASA Space Radiation Laboratory (NSRL) was used to simulate the patches of ionization. This new experiment brought about new problems.

The main problem involved the detection of reflections off of specific surfaces in the room itself. The room was cluttered with many surfaces for reflection. The first objective was to confirm reflection from antennas with time varying resistance. Reflection of a 100 MHz sinusoid off of the periodically varying real load gives rise to an amplitude-modulated signal. The appearance of sidebands at the harmonics of the fundamental frequency of the time varying load in the frequency spectra of the received signal confirms that reflection has occurred.

This simple experiment gave rise to additional problems. The equipment provided was poor; the oscillator had significant drift which made processing of the signal more difficult. Moreover, the spectrum analyzer was not calibrated. The initial phase of the experiment could only be performed when the beam was off which was typically late at night. In an ordinary room the group could have moved the antennas around as they pleased, however due to the high security of the provided area it was time consuming to go into the room and rearrange the antennas.

When the first stage of the experiment was over a similar approach was used to detect reflection off of the beam. The main periodic structure of the beam intensity occurred at a 2 MHz frequency. The periods of low intensity were shorter than the time required for electron recombination and therefore the main signature of the beam had no effect on the reflected power of the signal. The other periodicity of the beam occurred at three-second intervals. This extremely low frequency is difficult to detect and introduced a new set of problems.

Throughout the two semesters new problems emerged that changed the nature of the project. In the end the main goal was to perform an experiment that would confirm the reflection of radio frequency EM waves off of a beam of ionization with a 1/3 Hz time varying intensity.

## 3.2 FINAL IMPLEMENTATION

The problems encountered led to the development of the final experiment. Below are the 4 main parts to this experiment:

1. Confirm that reflection can be detected using the specific antennas and other equipment that was at our disposal.
2. Confirm that reflection could be detected using the same equipment in the beam room of NSRL with the beam off.
3. Confirm that low frequency low power reflection could be detected with the same equipment in the same room.
4. Confirm that Reflection off of the beam has occurred.

The first part appears elementary; however there was a fear that because of the close proximity of the antennas near field effects would be present and the reflected signal would not conform to established theory. Higher frequency transmissions would have provided smaller wavelengths however the physicists were concerned that if the frequency was too high that the performance would be too far from the 56 MHz commercial VHF signals being used for the eventual experiment.

| | |
|---|---|
| Biconical antenna (high beamwidth) | HP / Agilent 11955A EMCO 93110B |
| Log periodic antenna (highly directional) | Winegard PR-6000 |
| SPDT RF switch | Minicircuits TOSW-230 |
| Software radio receiver | IC PCR-100 |

*Table 1. Materials list*

Three antennas were employed. The transmitting and receiving antennas purchased were the log periodic antennas. These antennas were chosen for their high directivity, which was ideal for transmitting and receiving the maximum power to and from the desired surface. The reflecting antenna was a high beamwidth biconical antenna, which was suitable for receiving and reflecting signals from different directions.

A single pole double throw RF switch was used to transfer the load of the reflecting antenna between 50 ohms (matched impedance) and a short circuit. A function generator that was provided to us controlled the switch. In case reflection could only be detected by using the transmitting antenna as the receiver, a bi-directional decouple was purchased to separate the transmitted and received signals. Both the RF switch and the bi-directional decoupler were purchased from mini-circuits.com. Other materials for the initial phase included a signal generator to produce the transmitted signal, a spectrum analyzer, and SMA to BNC converters. All of these parts were provided by Tony Olivio and the experiment was performed in his lab.

Many of the same materials were used for part 2, although the scopes and signal generators were different and led to numerous problems. In the third and fourth part large amounts of data were collected and stored digitally. To store the data on a computer the PCR-1000 radio receiver was used to demodulate the signal and send it to the PC sound card. This radio receiver was especially helpful when used with the free compatible software TalkPCR and Spectrum Laboratory. The TalkPCR software allowed one to tune and even filter the data while the Spectrum Laboratory provided real time Fourier analysis. Table 1 contains a list of the main components used in the experiment.

The final two stages of the experiment required extensive signal processing that was simulated and eventually implemented using MATLAB. In order to detect the low power 1/3 Hz harmonics the data needed to be down-sampled. To down-sample a signal 120 times is analogous to decreasing the sampling rate by the same factor. Thus before the down-sampling could occur the signal needed to be shifted in frequency through modulation and filtered to prevent aliasing.

## 3.3 TESTING

Success in the first two parts of the experiment could be confirmed with the appearance of the appropriate sidebands on the spectrum analyzer. The latter sections required the storage of large amounts of data and more extensive processing with MATLAB.

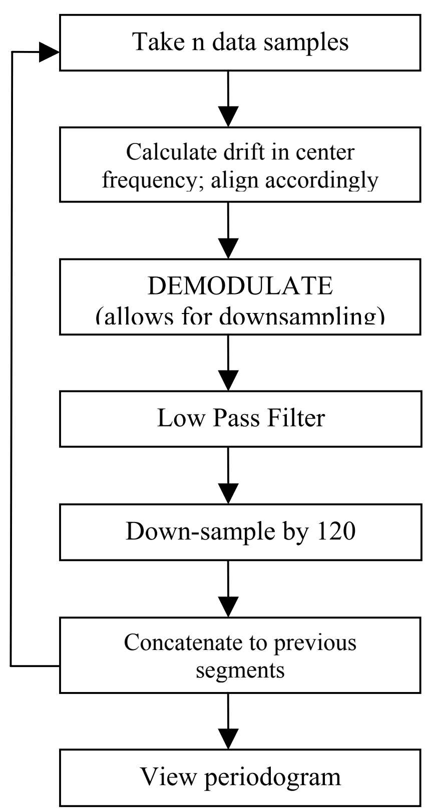


*Figure 3. Signal Processing*

Figure 3 depicts a flow chart of the process. When the data was first viewed the peaks of the received signal were very wide. The frequency of the oscillator had drifted considerably over time and this presented a problem. The solution was to segment the data and shift each portion to the center frequency of the first. This was accomplished through modulation, when the partitioned signals were downshifted to accommodate for down-sampling the frequency of the modulating signal was slightly altered based on the drift at that interval. Filtering was accomplished in a non-causal matter by simply windowing the function in the frequency domain. The signals were then down-sampled and concatenated in the time domain. A periodogram of the final concatenated signal would reveal if reflection had occurred.

# 4 RESULTS AND DISCUSSIONS

This chapter provides a brief description of the results obtained.

## 4.1 RESULT ANALYSIS

At the end of the experiment, analysis of the collected data was able to confirm the reflection off of the biconical antenna with 1/3 Hz modulation. Unfortunately reflection from the beam could not e confirmed. Figure 4 shows the results when the transmitting antenna is in front of the beam and the receiving antenna is in the tunnel on the right side of the room. This is the only configuration in which reflection could be confirmed at such a low frequency.

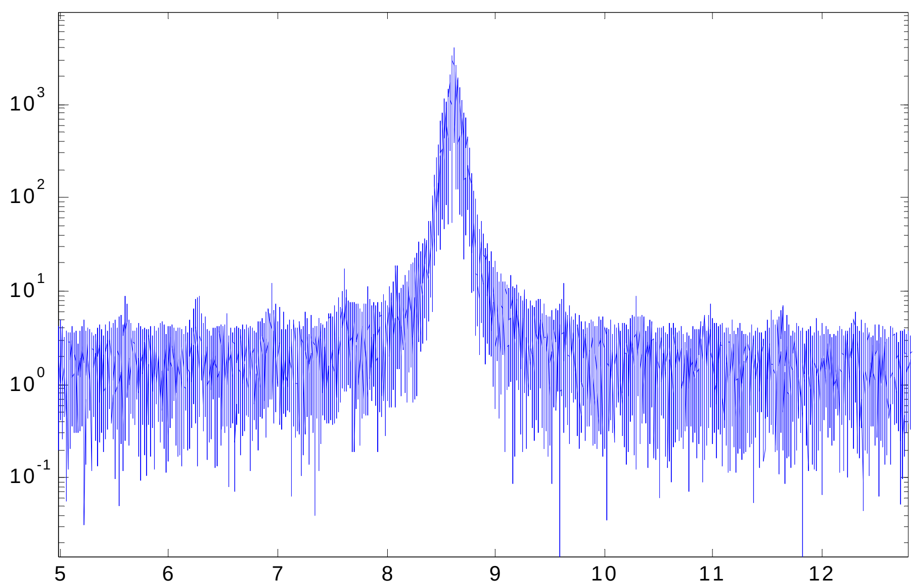


*Figure4. Obtained Spectrum*

Examination of the results in Fig.2 reveals equally spaced sidebands occurring at 1/3 Hz intervals symmetric with respect to the center frequency. Analysis of the data with the beam on does not produce the sidebands seen in Fig. 4. Thus reflection off of the beam has yet to be confirmed.

There are many explanations as to why reflection from the beam could not be detected. The obvious answer is that the 1/3 Hz structure in intensity was not sufficient enough to be detected with the given equipment. Moreover, the ionization density of the beam probably would not have been high enough to have provided the required surface area of $\lambda/2$ $m^2$.

Currently the beam is off; however when it goes back on the physicists intend to superimpose an additional 60 Hz structure on the beam. This may provide the necessary signature for reflection to be detected.

## 4.2 MULTIDISCIPLINARY ISSUE

The MARIACHI project is multi-disciplinary in nature, with physicists, electrical and computer engineers, computer scientists, and even high school students contributing. For the members of this group there was significant collaboration with physicists both from BNL and the Stony Brook physics department.

The MARIACHI project is headed by theoretical physicists. The members of this group met extensively with Professor Michael Marx and Helio Tekai, both of whom are physicists affiliated with Brookhaven. The physicists have broad understanding of the concepts behind the electrical engineering aspects of the project such as RF wave propagation and fourier analysis, however they require engineers to implement the experiment. On the other hand as engineers the member of the group were often unfamiliar with the theoretical physics that provided the background for the experiment, yet were able to grasp the core concepts necessary to perform the task at hand.

The interdisciplinary aspect of the project was the most appealing and most rewarding aspect of these two semesters. The members of the group spent many hours at

Brookhaven and in meetings with physicists. Being able to apply engineering concepts to other fields, especially scientific research, is a valuable experience.

## 4.3 PROFFESIONAL AND ETHICAL ISSUES

Ethical issues were not a major concern during our senior design project. However, during the second semester, experiments were performed at NSRL (NASA Space Radiation Laboratory). In order to gain access to this facility, our team underwent extensive preparation and testing on radiation safety. While we were inside the NSRL facility, we had to wear mandatory TLD tags. TLD tags are badges that are worn around a person's neck and their purpose is to record the dose of radiation a person receives which being inside a radiation facility. Although doses are low and harmless, this issue was taken into consideration. Due to the miniscule doses that we were exposed to, we concluded that the benefits outweighed any possible health effects.

## 4.4 IMPACT OF PROJECT ON SOCIETY

One of the main reasons that the National Science Foundation (NSF) agreed to fund the MARIACHI project was because of the enormous amount of people benefiting from this project. Most importantly, there are ten (10) high schools all over Long Island that are participating in this project. With the assistance of their teachers, students performed hands on assembly of the scintillation arrays that were mentioned earlier. During this process, the students will further develop their knowledge of physics. A website has been developed which displays results from the scintillation arrays in real time. This allows students to become more cyber savvy in a world that now revolves around the internet.

# 5 SUMMARY AND CONCLUSION

The data available at this date has yet to confirm reflection off of the beam. Experiments with the biconical antenna confirm that reflection can be detected from a 1/3 Hz amplitude modulated load in the beam room at NSRL. The effects of beam intensity on the reflection resistance are not fully understood, and thus more experiments must be conducted to determine if reflection has occurred. A new 60 Hz periodic structure will be superimposed on the beam when it is restarted. Despite this the project was very rewarding. The members of the group had the opportunity to work with extremely intelligent and knowledgeable people, both engineers and physicists. A great amount was learned in the areas of signal processing, communications, detection theory, and RFID. Some of this knowledge was not used for the eventual experiment, however it will undoubtedly find future use in the careers of the group members. The authors of this report gained valuable insight into the process of scientific research, gaining exposure to the many different people and tasks involved in MARIACHI. The opportunity to work on MARIACHI for senior design was an invaluable experience.

# ACKNOWLEDGEMENT

We are extremely indebted Prof. Djuric for providing us with an opportunity to have worked with him. We are grateful for the valuable advice and guidance he provided us with through the course of these two semesters. We would also like to thank Prof. Michael Marx at the physics department and Helio Takai at BNL for all the help and insight provided. We would also like to acknowledge the help received from everyone at NSRL, especially Michael Sivers and Adam Rubik. We are also thankful to graduate student Zejie Zhang and Tony Olivio for their valuable contribution.

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